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SMART COATINGS FOR DRAG REDUCTION IN YACHTS

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In some sailing conditions, the friction drag of a yacht hull can account for more than half of the total resistance. If the surface of the hull was not rigid but flexible as, for instance, the skin of a dolphin, it would be possible to decrease the friction drag considerably. Compliant walls can decrease the friction drag either by delaying the laminar to turbulent transition, or by interacting with a post-transition boundary layer. In the present work the second of these two mechanisms is explored. We study both actively and passively controlled surfaces with direct numerical simulations. We consider a canonical channel flow, where the boundary layer in the half channel represents a thin section of the hull's boundary layer. The friction Reynolds number of the boundary layer is $Re_\tau \approx 180$, and we show how the results can be scaled to higher Re_τ . We model the coating as an array of independent tiles, each attached to the hull by a spring and a damper, and free to move only in the streamwise or the spanwise direction. A drag reduction of 25% and 3% is achieved with an active and a passive control, respectively, of the proposed surface.

1 INTRODUCTION

The resistance of sailing crafts can be broken down into friction drag and pressure drag. The friction drag is higher than the pressure drag at low sailing speeds, and *vice versa* [1]. The pressure drag can be decreased by shape optimisation, while the friction drag is typically accounted for by minimising the wetted surface [2, 3, 4, 5, 6]. In fact, decreasing the friction drag for a given wetted surface is challenging.

Choi *et al.* [7] carried out experiments on a scaled model of Australia II, the yacht that won the 1983 America's Cup. The experiments showed that a combination of riblets and polymer additives can reduce the friction drag by as much as 3.5%. However, the riblets must be designed for a specific flow speed and direction, and outside of these conditions they lead to a drag increase.

Foeth [8] considered air lubrication of the hull. Air is kept around the hull by bubble injection, air cavities, or air films. This approach has similarities with the use of hydrophobic surfaces, which are known to enable drag reduction [9]. The air lubrication enables 20% drag reduction. Unfortunately, outside of the optimal flow conditions it can lead to drag increase, and the technological realisation is challenging.

In the present study we consider compliant coatings inspired by the dolphin skin [10]. Compliant walls can decrease the friction either by delaying the laminar to turbulent transi-

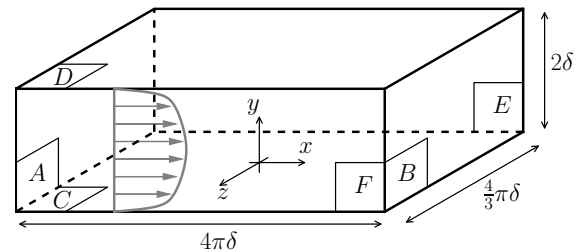


Figure 1: The computational domain and the coordinate system (not in scale).

tion, or by interacting with a post-transition boundary layer. The second of these strategies is the subject of this work. Choi *et al.* [11] and Kang&Choi [12] showed that *actively-controlled* wall-normal displacements of a compliant wall can enable drag reduction. This control, known as ‘opposition control’, is based on the flow velocity fluctuations in the near wall region. It was also proven, both analytically [13] and experimentally [14], that *passive* compliant coatings can reduce the friction drag by damping the turbulent fluctuations of a fully-turbulent boundary layer.

Recent studies, based on Direct Numerical Simulation (DNS), tried to reproduce these experimental results [15, 16]. The proposed passive coatings was deformed in the wall-

normal direction by the instantaneous variations of the fluid pressure. The drag reduction was not confirmed by these simulations. The pressure-driven deformations could not mimic the active wall-normal opposition control because the wall pressure is not correlated with the near-wall velocities. Indeed, this was also anticipated by the pioneering study of Choi *et al.* [11].

In this paper we consider in-plane deformations that are driven by the wall shear stresses. The wall shear stresses are directly correlated with the velocity field near the wall. The goal of our study is to identify beneficial coating dynamics, and quantify the corresponding drag reduction.

2 METHOD

We investigate turbulent channel flows with DNS. These high-fidelity computational fluid dynamics simulations allow the same confidence level as experimental measurements.

Symbols with the superscript plus (+) indicate quantities that are made dimensionless with the kinematic viscosity of the fluid ν , the friction velocity u_τ and the density ρ . Any other quantity is made dimensionless with the channel half height δ , the bulk velocity u_b and the density ρ . Angle brackets $\langle \rangle$ enclose time-averaged quantities, and the prime superscript (') indicates the zero-mean fluctuating component of a time-varying quantity. The dot superscript (·) stands for the temporal derivative.

Simulations were run on the UK national supercomputer ARCHER. The wall time of each simulation was around 14 hours using 288 cores from 12 Intel E5-2697 v2 Ivy Bridge processors.

2.1 SOLVER

We solve numerically the governing equations of Newtonian fluids for incompressible flow. The flow domain in a channel between infinite plates is discretised with a Cartesian grid (Figure 1). A fractional step method [17] is used for the time advancement, with a second-order implicit Crank-Nicolson scheme for the convective and the viscous terms in the wall-normal direction, and a third-order low-storage Runge-Kutta scheme for the other terms. The spatial derivatives are discretised with a second-order central finite difference scheme on a staggered grid. The pressure Poisson equation is solved directly using fast Fourier transforms in the two periodic directions. For a more detailed description of the numerical scheme and the implementation, we refer to the work of Balaras [18]. After the flow has become fully developed, the time step $\Delta t^+ \approx 0.115$ is kept constant. The presented statistics are the results of averaging over a period $t^+ \approx 23000$.

2.2 BOUNDARY CONDITIONS

The computational box is $4\pi\delta \times 2\delta \times 4\pi\delta/3$ in the streamwise, wall-normal and spanwise direction, respectively. The corresponding grid has a number of grid points $n_x \times n_y \times n_z = 290 \times 251 \times 290$.

Periodic boundary conditions are used on the domain faces A - B and F - E (Figure 1). For the baseline simulation of a

rigid wall, no-slip boundary conditions are prescribed on the C and D surfaces. As shown in the following two Sections (2.3 and 2.4), the no-slip boundary conditions are modified to study the effect of different active and passive coatings.

A time dependent streamwise pressure gradient is applied to keep the bulk Reynolds number $Re = u_b\delta/\nu = 2800$ constant in the channel. The friction Reynolds number of the rigid wall simulation is $Re_\tau = u_\tau\delta/\nu \approx 180$. As showed in Section 3.4, the results can be scaled to higher Re_τ based on the correlations between the coating dynamics and the turbulent statistics. In the rigid wall simulation, the Reynolds number based on the centre line velocity (u_c) is $Re_c = u_c\delta/\nu \approx 3300$. The centre line velocity represents the free-stream velocity of the water flow around the yacht. While u_b is the same for every simulation, u_τ and u_c depends on the resulting flow field.

The flow between the no-slip wall boundary C and the middle of the channel represents the boundary layer around the yacht hull. The periodic boundary conditions on the A - B surfaces allow to consider only a short streamwise section of the hull boundary layer without modelling its spatial development from the bow. Thus, the thickening of the boundary layer within the considered section is neglected. On the upper half of the channel, instead of a free-stream flow, a boundary layer symmetric in-the-average is modelled. For the purpose of the present investigation, this has a negligible effect on the boundary layer statistics.

2.3 ACTIVE CONTROL

To identify beneficial in-plane wall deformations and the corresponding maximum friction drag reduction, we consider actively-controlled in-plane wall displacements following the approach of Choi *et al.* [11]. The compressible coating is modelled by an array of independent tiles, where each tile corresponds to one grid cell. The velocity of each tile is set by the wall boundary condition. For the reference rigid simulation, the tile velocity is zero and we apply a no-slip boundary condition. We then consider one of the two following control strategies, where the local coating velocity is actively set based on the nearby flow velocity.

Active u' -control

The streamwise deformation velocity of the wall $\dot{\xi}$ at time step n is equal in direction and in magnitude to the streamwise velocity fluctuation u' from the previous time step at a distance y_c from the wall:

$$\dot{\xi}^n = u'|_{y_c}^{n-1}. \quad (1)$$

Active w' -control

The spanwise deformation velocity of the wall $\dot{\zeta}$ at time step n is opposite in direction and equal in magnitude with the spanwise velocity fluctuation w' from the previous time step at a distance y_c from the wall:

$$\dot{\zeta}^n = -w'|_{y_c}^{n-1}. \quad (2)$$

2.4 PASSIVE CONTROL

We model an anisotropic compressible coating as a series of tiles, which can overlap to each other. Each tile is independent by the adjacent tiles. The tile has a mass m and it is attached to the hull by a spring with a constant k , and a damper with a viscous damping coefficient c . The tiles are free to move only in the streamwise direction. The overlapping tiles are a discrete model of a continuous compressible coating. Overlapped tiles indicate a region where the coating is compressed, and separated tiles indicate a region where the coating is stretched.

Each tile corresponds to one grid cell on the wall and has a surface area $\Delta x \Delta y$. At every time step, for each tile we solve the streamwise wall deformation ξ , the velocity $\dot{\xi}$ and the acceleration $\ddot{\xi}$ due to the force $F = \tau_x \Delta x \Delta y$, where τ_x is the streamwise wall shear stress. Therefore the boundary condition of the passive coating can be written as

$$m\ddot{\xi}^n + c\dot{\xi}^n + k\xi^n = F^{n-1}. \quad (3)$$

A passive spanwise control has not been considered. In fact, in the passive control, the wall velocity is driven by the wall shear stress, which has the same direction as the near-wall velocity. Once the wall has reached the initial deformation due to the mean flow, the wall velocity *fluctuation* has the same direction as the near-wall velocity *fluctuation*. This suggests that spanwise passive control cannot mimic the active w' -control, where the wall velocity fluctuation has opposite direction as the near-wall velocity fluctuation (cf. equation 2).

3 RESULTS AND DISCUSSION

The drag reduction (DR) is used to quantify the control efficiency and it is defined as

$$DR = \frac{\Delta p_{\text{controlled}} - \Delta p_{\text{rigid}}}{\Delta p_{\text{rigid}}}, \quad (4)$$

where Δp denotes the time-averaged pressure drop through the channel.

3.1 VALIDATION OF THE REFERENCE CASE

The reference simulation with a rigid wall is validated against the DNS simulation of Moser *et al.* [19]. Figure 2 shows the Root Mean Square (RMS) of the streamwise velocity fluctuations (u'), the wall normal velocity (v') and the spanwise velocity (w') across the boundary layer. All velocity statistics show a good agreement with Moser *et al.* Excellent agreement is also found for the Reynolds stress $\langle u'v' \rangle$.

3.2 ACTIVE CONTROL

We search for the optimal control distance y_c that enables the two active controls described by equations 1 and 2. Figure 3 shows the drag reduction as a function of y_c . The u' -control results in a peak drag reduction around 8% at $y_c^+ = 8$. The w' -control is more efficient than the u' -control, with a peak drag reduction around 25% at $y_c^+ = 12$. These results are in qualitative agreement with those of Choi *et al.* [11], who

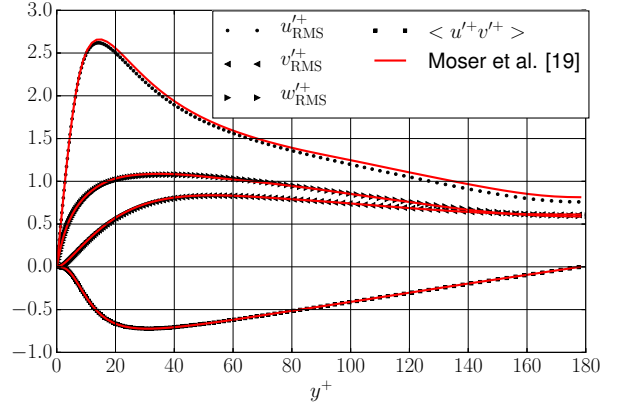


Figure 2: Validation of the turbulent statistics of the rigid wall simulation against literature data.

found that the peak drag reduction with the u' - and the w' -control were around 10% and 30%, respectively. They found an optimal control distance of $y_c^+ \approx 10$ for both controls. We believe that the differences in the control efficiency are probably caused by the detailed of the implementation, for instance by the phase lag of one time step between the measured signal and the actuation (see equations 1 and 2).

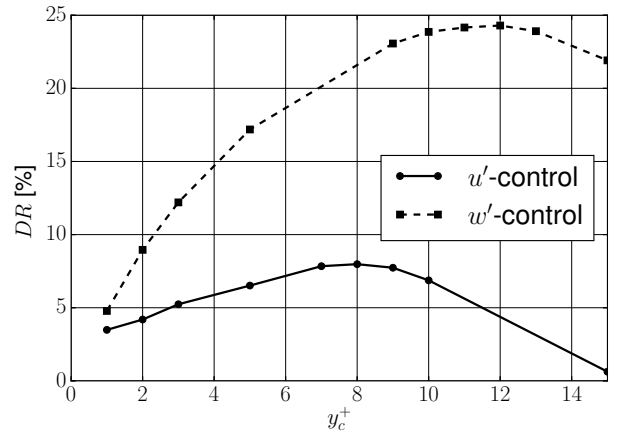


Figure 3: Drag reduction of the active controls as a function of the control distance.

3.3 PASSIVE CONTROL

The simulations of a wide range of coating parameters m , c and k suggest that the maximum drag reduction is around 3%. Further research is currently ongoing to identify the optimal coefficients and the corresponding drag reduction. In the following, we analyse the flow field achieved with a set of parameters ($m = 15\Delta x \Delta y / \text{Re}_b$, $c = \Delta x \Delta y / \text{Re}_b$ and $k = \Delta x \Delta y / \text{Re}_b$) that results in a drag reductions of 2.87%.

The deformation of the coating has only a small influence on the pressure gradient, while it causes well distinguishable changes in the turbulent statistics. Figure 4 shows the first component of the Reynolds stress tensor $\langle u'u' \rangle$ the RMS of the wall-normal vorticity fluctuations ω_y' and of the span-

wise vorticity fluctuations ω'_z . Since the wall of the compliant coating is moving in the streamwise direction, at the wall $\langle u'u' \rangle \neq 0$. This results in a higher peak of $\langle u'u' \rangle$ in the buffer layer compared to the rigid wall. The spanwise vorticity fluctuation $\omega'_z = \partial v'/\partial x - \partial u'/\partial y$ is dominated by the second term, $-\partial u'/\partial y$. As the coating moves in the streamwise direction, the wall-normal gradient of the streamwise velocity fluctuations ($\partial u'/\partial y$) drops down, and results in a decreased spanwise vorticity.

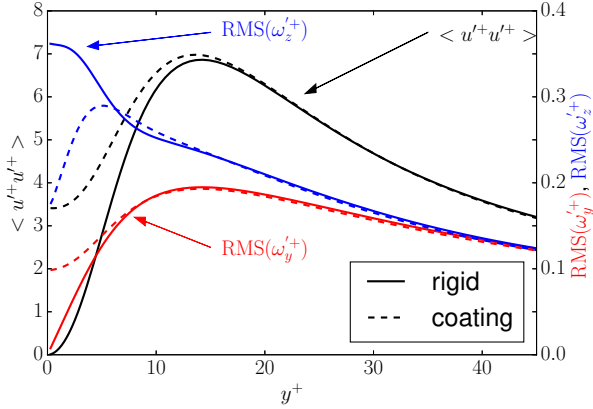


Figure 4: Velocity and vorticity statistics in the first quarter of the boundary layer.

The high and low momentum regions of the streamwise velocity, also known as buffer-layer streaks, are one of the most distinctive flow features of turbulent boundary layer flows [20]. These high and low momentum regions leave a footprint on the wall shear stress at the wall. The streamwise high and low shear regions are visualised in Figure 5 by the contours of the wall-normal gradient of the streamwise velocity fluctuation at the wall. Since the wall deformation velocity tries to follow the shear originating from the streaks, the wall velocity also shows a similar pattern than the wall shear stress (Figure 6). The wall velocity results in higher production of wall-normal vorticity fluctuation near the wall: $\omega'_y = \partial u'/\partial z - \partial w'/\partial x$.

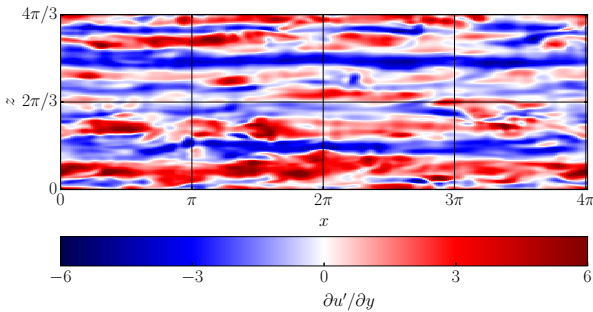


Figure 5: Instantaneous distribution of the wall-normal gradient of the streamwise velocity fluctuation at the wall.

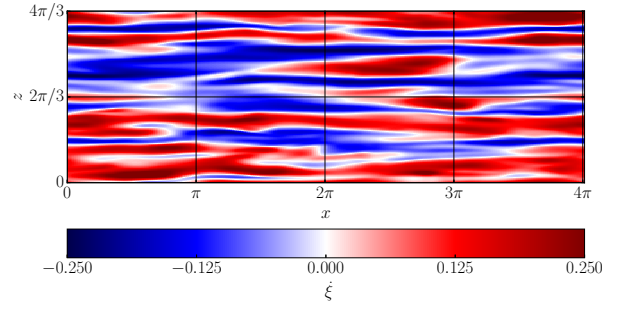


Figure 6: Instantaneous deformation velocity of the coating.

3.4 SCALING AND RESULTS

Our results show that the tile spacing and dynamics should be correlate with those of the streaks. The streaks scale with the wall variables ν/u_τ and u_τ . The spanwise spacing of the streaks is roughly $100 \nu/u_\tau$. The streamwise spacing varies from $1000 \nu/u_\tau$ to $10\,000 \nu/u_\tau$ [21]. To estimate the required tile spacing for a full scale yacht under realistic sailing conditions, we assume that the deformations and the deformation velocities of the coating scale with those of the streaks.

Using a $1/7^{\text{th}}$ power law [22], we can estimate the friction Reynolds number (Re_τ) along different positions of the hull, for different sailing speeds. The viscous length scale ν/u_τ decreases with the sailing speed, and increases with the distance from the bow. Recalling that the present simulations have been performed at $Re_\tau \approx 180$, our results are representatives of the boundary layer at 0.2 m and 0.02 m from the bow for a sailing speed of 1 m/s and 5 m/s, respectively. Let scale our results to the boundary layer at 10 m from the bow of a yacht sailing at 5 m/s. In these conditions, the boundary layer thickness is ca. 0.12 m, the friction Reynolds number is $Re_\tau = 2 \cdot 10^4$ and the viscous length scale is $6 \cdot 10^{-6}$ m. The spanwise tile spacing should be lower than the streak spacing, which is $6 \cdot 10^{-4}$ m. Scaling the deformation velocity of the wall with the friction velocity, we find that tiles within a spanwise distance of 0.5 millimetre would move in opposite directions with an average streamwise velocity of 0.3 m/s. Scaling the deformation based on the viscous length scale, leads to a maximum streamwise deformation of $5 \cdot 10^{-3}$ m.

Assuming that the drag reduction is the same at higher Reynolds numbers, we can estimate the speed gain enabled by a 3% drag reduction. Let consider, for instance, an America's Cup Class yacht. This class was used in the America's Cup from 1992 to 2007. At the typical upwind speed of 5 m/s, the friction drag is approximately half of the resistance [6]. In these conditions, a 3% change in the friction drag would result in a speed increase of almost 1%.

4 CONCLUSIONS

We investigated the potential hydrodynamic drag reduction of compliant coatings. We performed direct numerical simulations of a fully turbulent channel flow at friction Reynolds number $Re_\tau \approx 180$ and we scaled the results to higher Reynolds number conditions. We modelled the hull surface

as an array of tiles. Each tile is smaller than a squared viscous length and can move only in the streamwise or spanwise direction, depending on the control.

We found that, if the in-plane displacement of each tile is actively prescribed based on the flow velocity fluctuations at $y^+ \approx 10$, than the friction drag would decrease by up to 25%. We also considered a compliant coating that was passively deformed by the streamwise wall shear stress. Each tile is attached to the hull by a spring and a damper, and free to move only in the streamwise direction. This passive anisotropic coating enabled a drag reduction of ca. 3%.

The drag reduction is the result of the interaction of the coating with the buffer-layer streaks. Noting that the scalability of these flow features with the Reynolds number is well established, it is possible to scale the present results to higher Reynolds numbers. As an example, we scaled the results for a hull section at 10 m from the bow and a sailing speed of 5 m/s. We found that two points of the passive coating, that are less than half millimetre apart in the streamwise direction, would move in opposite directions with an average velocity of 0.3 m/s. Each point would move by maximum $5 \cdot 10^{-3}$ m.

For an America's Cup Class monohull, this passive coating would enable a speed increase of about 1%. Ongoing research aims to identify a passive coating, with different mechanical properties, that would enable higher drag reduction.

5 ACKNOWLEDGEMENT

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Mr Tamás István Józsa is a PhD student at the University of Edinburgh, working under the supervision of Dr Viola. He earned a mechanical engineering bachelor's degree at the Budapest University of Technology and Economics (BUTE) and two master's degrees in mechanical engineering modelling and in computational fluid dynamics at BUTE and Cranfield University. His current PhD project aims to investigate the skin friction reduction potential of compliant coatings for marine applications. The supervisory team includes Prof. Kashtalyan, Dr Kidd and Prof. Balaras. Mr Józsa has been the recipient of numerous awards, including the Pattantyús-Pálffy Prize for the best bachelor's thesis with a hydrodynamics topic at BUTE; a travel grant from International Paint Ltd.; an EPSRC ARCHER RAP award; the best poster in the Marine Energy Theme at the 2016 ETP Annual Conference; and the Principals Go Abroad Fund. He has been a Visiting Scholar at the George Washington University for 2 months in 2015 and 2 months in 2017.

Dr Ignazio Maria Viola is Senior Lecturer at the Institute for Energy Systems of the School of Engineering, University of Edinburgh and a Fellow of the Royal Institution of Naval Architects. He is Editor-in-Chief of the *Journal of Sailing Technology* (SNAME), and Member of the Editorial Board of *Ocean Engineering* (Elsevier) and the *International Journal of Small Craft Technology* (RINA). His background is in yacht sail aerodynamics, and his current research focuses on the control of vortical flow structures by means of flexible surfaces. He wrote more than 100 scientific publications and was awarded two RINA Medals of Distinctions and a RINA Medal of Exceptional Merit.

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Prof. Elias Balaras is a Professor at the Department of Mechanical and Aerospace Engineering at the George Washington University. His current research program aims at the development of robust numerical techniques for parallel, large-scale simulations of multiscale, multiphysics problems in physical and biological systems. Emphasis is given at large-eddy and direct numerical simulations, fluid-structure interactions and biological fluid dynamics. He has been the recipient of several awards including the Marie-Curie fellowship from the European Commission in 1994 and the CAREER award from the National Science Foundation in 2003. Dr. Balaras has published over 100 papers in refereed journals and conference proceedings, and served as reviewer for numerous journals and government programs related to fluid mechanics, biological flows, high performance computing and turbulence. His research has been featured in several media outlets, including the *New York Times* and the *Sunday Times*.

Dr Barry Kidds is a Section Manager at AkzoNobels Marine Coatings business (International Paint Ltd.) based in the UK. He graduated from Heriot-Watt University with an Honors degree in Applied Chemistry followed by a PhD from The University of Manchester, Institute of Science and Technology. Barry has over 20 years of experience in the research and development of coatings technologies with current focus on fouling control coatings. Barry has led several technical projects with the aim of developing new products as well as managing the development of AkzoNobels marine coatings R+D laboratory in Singapore. Over the last 6 years Barry has managed the Hydrodynamics Team which focusses on developing a greater understanding of how fouling control selection affects ship efficiency. AkzoNobel create everyday essentials to make people's lives more liveable and inspiring. Team AkzoNobel is the first to enter the forthcoming edition of Volvo Ocean Race.